HIGH EFFICIENCY, ERROR MINIMIZING CODING STRATEGY METHOD AND APPARATUS

FIELD OF THE INVENTION

5   The present invention relates to coding data. In particular, the present invention

relates to a method and apparatus for encoding data that is highly efficient, and that

minimizes the effect of errors.

BACKGROUND OF THE INVENTION

10   Coding schemes are regularly used in connection with the transmission of data.

For example, in digital communication systems, data is typically transmitted as a series

of code words. In general, each code word is assigned a unique pattern of bits, with each

bit consisting of either a zero or a one. In most such digital communication systems, the

number of bits that may be used to define code words is limited. Therefore, it is desirable

15   to encode data such that a maximum number of code words (*i.e.*, bit patterns) are

available as code words. It is also desirable to reduce the effect of errors that may occur

in transmitting code words across the communication channel.

In many digital systems, errors in the detection, transmission or reading of bit

patterns may occur. For example, certain bit patterns may result, on occasion, in certain

20   bits being "flipped." The particular bit patterns that are susceptible to flipping are

generally determined by the system under consideration. Such errors may be identified as

dominant errors if they are much more likely to occur than errors due to random effects,

such as noise.

In a typical coding scheme, a code word that is read incorrectly due to the

occurrence of a dominant error can result in a very large discrepancy. That is, the value of the original code word can be very different from the code word that is actually read. In general, this is because the strategies used to assign values to code words do not take into consideration the dominant errors that may be associated with a system.

5   Modulation codes have been used to aid in the transmission and reception of data. Such codes are designed to avoid code words that are particularly susceptible to being misread. For example, code words having a string of identical bits of at least a certain length may be susceptible to detecting one or more of the bits as its opposite. A modulation code designed to avoid such a "bit flipping" event may eliminate as valid

10   code words any pattern of bits that includes more than the allowed number of identical bits in a row. However, such "run length limited" codes reduce the efficiency of the code space by eliminating what would otherwise be valid code words.

Coding schemes have also been developed to detect, and in some instances correct, errors that occur during the transmission and reception of the data. Error control

15   codes include parity checking codes and error correction codes. In a typical parity code, an extra bit is assigned to tracking whether the detected code word should contain an even or odd number of '1' bits. Upon detection of the code word, if the parity code does not agree with the code word (e.g., the detected code word contains an even number of 1's, but the parity code indicates that it should contain an odd number of 1's), it can be

20   assumed that an error occurred during transmission or reception of the code word. If the coding scheme used is a simple parity checking scheme, no correction is generally possible, and the received code word is discarded.   In a typical error correcting code,

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more than one parity or error control bit is used to enable at least some errors to be

corrected. However, each bit of a code word dedicated to parity checking or to error

correction reduces the efficiency of the coding scheme.

As an example of systems that include a communication channel susceptible to

5   dominant errors, a computer hard disk drive system and a voice communication system

will be described. However, it should be appreciated that the present invention is not

limited to use in connection with such systems, and can generally be applied to any

communication system that is susceptible to dominant errors and that can tolerate some

deviation between a value as written and a value as read.

10   With reference now to **Fig. 1**, a typical disk drive system **100** is illustrated. The

disk drive system **100** is operative for performing data storage and retrieval functions in

connection with an external host computer (not illustrated in **Fig. 1**). The disk drive **100**

generally includes a base **104** and magnetic disks **108** (only one of which is shown in **Fig.**

1). The magnetic disks **108** are interconnected to the base **104** by a spindle motor (not

15   shown) located within or beneath the hub **112**, such that the disk **108** can be rotated

relative to the base **104.** Actuator arm assemblies **116** (only one of which is shown in

Fig. 1) are interconnected to the base **104** by a bearing **120.** The actuator arm assemblies

116 each include a transducer head **124** at a first end, to address each of the surfaces of

the magnetic disks **108.** A voice coil motor **128** pivots the actuator arm assemblies **116**

20   about the bearing **120** to radially position the transducer heads **124** with respect to

magnetic disks **108.** Voice coil motor **128** is operated by a controller **132** that is in turn

operatively connected to the host computer (not shown). By changing the position of the

transducer heads **124** with respect to the magnetic disk **108**, the transducer heads **124** may

address different tracks or cylinders **136** on the magnetic disk **108**. The disk drive **100**

also generally includes a channel **138** for receiving and decoding data read from the disk

108 by the transducer heads **124**.

5   Typically, the data is stored in the concentric tracks **136** as a series of magnetic

transitions. In an ideal disk drive system **100**, the tracks **136** are non-perturbed circles

situated about the center of the disk **108**. As such, each of these ideal tracks includes a

track centerline that is located at a known constant radius from the disk center. In an

actual system, however, it is difficult to write non-perturbed circular tracks **136** to the

10   data storage disk **108**. That is, problems such as vibration, bearing defects, inaccuracies

in the servo track writer used to write the tracks **136** and disk clamp slippage can result in

tracks **136** that are written differently from the ideal non-perturbed circular track shape.

The resulting inaccuracies in the shape of the tracks **136** due to such errors is known as

written-in and repetitive runout. The perturbed shape of these tracks **136** complicates the

15   positioning of the transducer heads **124** during read and write operations because the disk

drive servo system needs to continuously reposition the transducer heads **124** during

track following.

    In order to at least partially correct the shape of the tracks **136** and to minimize the

effects of written-in and repetitive runout, the tracks **136** are periodically encoded with

20   embedded run-out correction (ERC) values. In particular, the embedded run-out

correction values serve as corrections to the position error signal (PES) generated during

track following.

Although the correction values stored in the ERC fields represent discreet correction amounts, the amount of correction need not be precisely read in order to usefully alter the position error signal read from a track **136** during track following. However, conventional disk drive systems utilizing embedded run-out correction

5   typically discard embedded runout correction values that are not correctly detected by a detector included as part of the channel **138.** Accordingly, previous systems have treated embedded runout correction values, which can tolerate at least some variance between the value as originally written and the value as detected, in the same way as user data, which generally must be discarded if errors in the reading of such data occur. Therefore, such

10   conventional methods result in inefficiencies and/or the loss of useful data.

As a further example of a system that includes a communication channel susceptible to dominant errors but that tolerate some variance between an intended value and a received value, consider a digital voice communication system. In general, a human listener is capable of comprehending the meaning of another's speech, even

15   though small portions of the conversation are lost, for example, due to transmission errors. However, breaks in an audible signal due to such errors are annoying and can make a conversation difficult or impossible to follow. Furthermore, typical communication channels used for transmitting voice data are susceptible to dominant errors. In addition, such systems must operate with high efficiency in order to be

20   economical. Therefore, communication systems used for the transmission of voice data could benefit from a coding strategy that minimized the effect of dominant errors in the communication channel, while reducing or eliminating the need to transmit redundant code.

As mentioned above, modulation and error control coding schemes require the recordal and transmission of redundant information in addition to the user data. Although this redundant information allows for the reduction, detection or correction of errors in the transmission of user data, the storage and/or transmission capacity of the system is

5   reduced. In addition, errors that are not detected result in values that may be very different from the intended value. Furthermore, errors that are detected but are not corrected may result in a code word being discarded, with no benefit being derived from the transmission of the discarded data. Therefore, it would be advantageous to provide a coding strategy that was highly efficient, and that minimized the effects of errors. In

10   addition, it would be advantageous to provide a system that could be implemented at low cost, and that was reliable in operation.

SUMMARY OF THE INVENTION

In accordance with the present invention, a high efficiency, error minimizing coding strategy is provided. The present invention may be used in connection with any

15   system that is susceptible to at least one dominant error in the transmission of data, and that can tolerate at least some deviation between a user value as recorded or transmitted and a user value as read or received. The coding strategy of the present invention allows data to be encoded such that errors are minimized, while maximizing the efficiency of the system.

20   According to one embodiment of the present invention, the dominant error or errors present in the communication channel of a system are identified. A list of code words of a length accommodated by the system is prepared, and each code word in the list

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is analyzed to determine its neighbor words. A neighbor word is the code word that is read by the system if a dominant error occurs during the reading or transmission of the code word under analysis. In addition, the code words may be grouped according to code words that are interdependent on one another. A code word is interdependent with

5   another code word if one of the code words is a neighbor of the other, or is related to the other code word because they are part of the same web or chain of neighbor words. Also, a maximum tolerable deviation range between a user value as encoded and a user value as decoded should be determined. If any group of code words includes a word that is directly interdependent with (*i.e.* is a neighbor of or to) a number of neighbor words

10 greater than two times the range of the maximum tolerable deviation between the user value as intended and the user value as received, a code word or words is removed from the coding scheme. The particular code word or words removed is chosen so that the requirement that no one code word is a neighbor of or to more than two times the maximum tolerable deviation range is met without removing more code words than is

15 necessary. The code words may again be grouped according to code words that are interdependent. Each code word in a group of code words may then be assigned a user value such that if a dominant error causes a first code word to be read as a second code word, the difference between the user value of the intended code word is within the range of tolerable deviation from the user value of the code word that was read. Any code

20 words not belonging to any group may be assigned to any remaining user values.

According to one embodiment of the present invention, a plurality of user values may be assigned to a single code word, so long as the user values are within the

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maximum tolerable deviation between user values established for the system.

According to another embodiment of the present invention, a first dominant error event for a communication channel is identified. A range of user values corresponding to a maximum tolerable user value error is also determined. Next, a first user value is

5   assigned to a first code word. A second user value, within the maximum tolerable user value error from the first user value is assigned to a second code word. The second code word is the word that is read as a result of the occurrence of the first dominant error upon the transmission of the first code word across the communication channel. In addition, a third user value may be assigned to a third code word. The third user value is, according

10   to an embodiment of the present invention, outside of the range of user values corresponding to a maximum tolerable user value error. Furthermore, the first code word is not read as the third code word if the first dominant error occurs.

According to still another embodiment of the present invention, a second dominant error for the communication channel is identified. A user value may be

15   assigned to the second code word that results if the second dominant error occurs during transmission of the first code word. According to the present invention, the user value assigned to the second code word should have a value that is within the range of maximum tolerable user value error from the first code word.

According to a further embodiment of the present invention, an apparatus having

20   or using data encoded according to an error minimizing scheme is provided. The apparatus includes a channel that is subject to at least a first dominant transmission error. The apparatus further includes a decoder in which a first code word is read as a second

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code word upon an occurrence of the first dominant error. The second code word has a user value that is within a range of user values corresponding to a tolerable amount of error in the apparatus from the first code word. According to still another embodiment of the present invention, the occurrence of the first dominant transmission error does not

5   result in the first code word being read as any code word that is outside of the range of tolerable error in user values.

Based on the foregoing summary, a number of salient features of the present invention are readily discerned. A method for providing a high efficiency, error minimizing code is provided. The method enables a system having a dominant error or

10   errors and that can tolerate at least some deviation between user values or data as stored or transmitted and user values or data as read or received to operate with high efficiency. Furthermore, the method of the present invention allows the maximum deviation between user values or data as stored or transmitted and user values as read or received due to a dominant error to be constrained to a chosen deviation amount. In addition, the

15   present invention provides an apparatus in which errors in the transmission or reading of user values or data results in user values that are within a defined maximum tolerable deviation. The apparatus achieves this without requiring the use of redundant data.

Additional advantages of the present invention will become readily apparent from the following discussion, particularly when taken together with the accompanying

20   drawings.

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BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a top view of a conventional computer disk drive, with the cover removed;

Fig. 2 is a block diagram depicting the relationship between an original signal, a communication channel and a received signal;

Fig. 3 is a flowchart illustrating the implementation of a high efficiency, error minimizing coding scheme in accordance with an embodiment of the present invention;

Fig. 4 illustrates a five bit code and the neighbor words that occur as a result of exemplary first and second dominant errors;

Figs. 5A-5F illustrate groups of interdependent code words from the example in **Fig. 4**;

Figs. 6A-6F illustrate groups of interdependent code words after the elimination of problematic code words from the example of **Fig. 4**;

Figs. 7A-7F illustrate groups of user values corresponding groups of interdependent code words illustrated in **Figs. 6A-6F**;

Fig. 8 is a table illustrating an example coding scheme in accordance with an embodiment of the present invention; and

Fig. 9 is a table illustrating an example coding scheme in accordance with another embodiment of the present invention.

DETAILED DESCRIPTION

With reference now to **Fig. 2**, the relationship between an original signal **200**, a communication channel **204** and a received signal **208** is illustrated. In general, the

original signal **200** is subject to alteration by the communication channel **204** to result in

a received signal **208** that is not identical to the original signal **200**. As will be

appreciated by those of ordinary skill in the art, the original signal **200** may be a signal

read from storage, or a signal provided for transmission. As will further be appreciated

5   by those of ordinary skill in the art, the communication channel **204** may comprise any

apparatus for conveying information. Examples of communication channels **204** include

voice data transmission systems, such as the plain old telephony system, a wireless

communication channel for transmitting voice or data, a computer network, or a read

element in combination with a detector, such as the transducer head **124** of a disk drive

10   **100** in combination with a detector included as part of the disk drive channel **138**.

According to the present invention, communication channel **204** must be subject

to an identifiable dominant error or set of errors. A dominant error is an error having a

high probability of occurrence. In particular, a dominant error has a much higher

probability of occurrence than a non-dominant error. More particularly, a dominant error

15   has a higher probability of occurrence than a random error. Furthermore, a dominant

error is distinct from a random error in that the effect of an occurrence of a dominant

error has a particular and identifiable effect.

With reference now to **Fig. 3**, an initial step in producing a code in accordance

with the present invention is to determine the size of the code space (step **300**). In

20   general, the code space of a system is equal to the base or radix (r) of the number system

used to the qth power (r^q), where q is the number of digits supported by the code. For

example, a system that is binary and that uses q number of bits in each word has a code

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space of 2^q. The code space of the system is initially equal to the data space, as at this point it is assumed that all of the code space is available for association with user values or data.

Another initial step in preparing a code in accordance with the present invention is to determine the dominant error events in the system, and the effect that occurrence of each of the dominant error events has on the code words (step **304**). In particular, those code words that are susceptible to being altered by the occurrence of a dominant error are identified. If the system is capable of transmitting code words sequentially, the effect of dominant error events on the code words must be determined when the code word is concatenated with other code words, as well as when the code word is transmitted across the channel singly.

As yet another initial step, the maximum tolerable deviation between a user value as written or transmitted and that user value as read or received is determined. According to the present invention, alterations to code words due to dominant errors result in received signals **208** having values that are the same or close (*i.e.* within the maximum tolerable deviation) to the values of the original signals **200**. In general, the greater the range of tolerable deviation, the more efficient the code scheme can be. That is, usually fewer code words will need to be eliminated as valid code words, as will be explained in greater detail below, if the maximum tolerable deviation is relatively large.

Following the initial steps **300**, **304** and **308**, which can be taken in any order, the code words that are susceptible to alteration by the identified dominant errors are placed into groups of interdependent code words (step **312**). In general, groups of

interdependent code words are formed from code words that are neighbor words or that are related to one another through one or more neighbor words. A first code word is a neighbor of a second code word if the occurrence of one or more dominant errors in the communication channel **204** causes the first code word to be read or received as the

5　second code word. In developing a code in accordance with the present invention, it is convenient to develop state diagrams consisting of interdependent code words, as will be explained below.

As a next step, the maximum tolerable deviation between user values as written and user values as received may be multiplied by two to determine the maximum number

10　of code words that can directly interdepend with any one code word (step **316**). Code words are directly interdependent if one code word is the neighbor of another code word. If this maximum number of directly interdependent code words is exceeded, code words are removed from the code space so that no code word having more than this number of directly interdependent code words remains in the code space.

15　User values are then assigned to the code words such that the occurrence of a dominant error in the transmission of an original signal **200** results in a received signal **208** that is within the maximum tolerable deviation of the original signal (step **320**). In this way, the occurrence of a dominant error in the communication channel **204** results in a user value that is acceptably close to the user value of the original signal **200**.

20　Accordingly, the coding scheme constrains the effect of dominant errors in a communication channel **204**, such that a useful user value is provided to the system despite the occurrence of a dominant error or errors. Furthermore, the coding strategy of

the present invention achieves this without requiring the use of redundant bits.

As an example of dominant errors, the channel **204** of a system using a five bit binary code space may have a first dominant error event that transforms an original signal **200** of 10001 to a received signal **208** of 10101. That is, the first dominant error,

5   according to this example, results in flipping the middle of three bits having a value of zero and bounded on either side by bits having a value of 1. In addition, the channel **204** of the system may have a second dominant error that transforms an original signal **200** of 01110 to a received signal **208** of 01010. That is, the second dominant error results in the flipping of the middle bit when three bits having a value of one are bounded on either

10   side by bits having a value of 0.

Where code words are capable of being transmitted in series, the effect of dominant error events must be considered for each code word when it is concatenated with any other code word. For example, a code word having an original signal equal to 00011, having a decimal equivalent of 3, can be read as received signal 01011, having a

15   decimal equivalent of 11, when a code word ending in 1 precedes the original signal and the first dominant error event occurs. Likewise, a received signal of 00010 can result when the original signal of 00011 is followed by a code word having a first bit equal to 1 and a second bit equal to 0 and the second dominant error event occurs. In addition, an original signal of 00011 can result in a received signal of 01010 if the code word is

20   preceded by another code word ending in one and the first dominant error occurs, and is followed by a code word beginning with the bits 10 and the second dominant error also occurs.

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With reference now to **Fig. 4**, a five bit code having user values equal to the decimal equivalent of the binary code is illustrated. In particular, column 1 illustrates user values **400** and the second column contains the binary code decimal equivalent **404** for each code word **408**. According to the code illustrated in **Fig. 4**, the user values **400**

5   are equal to the binary code decimal equivalents **404** of the code words **408**. The third column contains the code words **408** in binary code. The fourth column **412** identifies the user values **400** of neighbor words for each code word **408**. For the code illustrated in **Fig. 4**, the communication channel **204** of the system is assumed to have two dominant errors, in which the first dominant error transforms an original signal **200** of 10001 to a

10   received signal **208** of 10101, and in which a second dominant error transforms an original signal **200** of 01110 to a received signal **208** of 01010. Given these two dominant errors, none of the code words has more than three neighbors **412**. The last column in **Fig. 4** shows the maximum variance **416** between the user value **400** of the original signal **200** and the user value **400** of the received signal or signals **200**.

15   As is evident from the maximum variance **416** values for the code illustrated in **Fig. 4**, certain of the code words **400** may be transformed by the occurrence of a dominant error into a neighbor code word having a user value **400** that is 16 less or 17 more than the user value **400** of the original code word. For example, an original signal **200** having a binary code **408** of 11011 and a user value **400** of 27, may be transformed

20   into a received signal **208** having a binary code **408** of 01010 and a user value **400** of 10 if it is preceded by a code word ending in 01 and the second dominant error then occurs. Similarly, an original signal **200** having a binary code **408** of 00100 and a user value **400**

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of 4 may be transformed into a received signal **208** having a binary code **408** of 10101 and a user value **400** of 21 if it is preceded by a code word ending in 10 and succeeded by a code word beginning in 01, and the first dominant error of the communication channel **204** occurs twice.

5   With reference now to **Figs. 5A-5F**, groups of interdependent code words from the example code illustrated in **Fig. 4** are shown. As depicted in **Figs. 5A-5F**, the groups of interdependent code words may be considered as state diagrams, in which movement within the group results from the occurrence of one or both of the dominant error events for the system. In general, the groups depicted in **Figs. 5A-5F** are formed by grouping

10   code words and their related directly interdependent code words (*i.e.* neighbor words) to form a larger group of interdependent code words.

        With reference now to **Fig. 5A**, it can be seen that an original signal **200** that includes any one of eight different binary codes **408** can result in a received signal **208** having a binary code decimal equivalent **404** of 10. Similarly, as shown in **Fig. 5B**, any

15   one of eight different binary codes **408** can be altered in the channel **204** by the occurrence of one or more of the dominant events so that the received signal **208** has a binary code decimal equivalent **404** of 21. As illustrated in **Figs. 5C-5F**, the occurrence of a particular code word **408** as an original signal **200** may result in a corresponding other received signal **208** upon the occurrence of certain of the dominant error events.

20   According to the present example, the maximum tolerable deviation between user values is assumed to be one. Therefore, no valid code word **408** may have more than two other code words **408** that are directly interdependent with it. As stated previously,

binary codes **408** are considered to be directly interdependent with one another if a first of

the code words **408** may be altered by the occurrence of a dominant error in the

communication channel **204** such that the received signal **208** is the second of the code

words **408**.

5   Because the groups illustrated in **Figs. 5A** and **5B** each have code words that

directly interdepend with more than two other code words, it is necessary to remove code

words until this no longer the case. As can be appreciated by considering the groups

illustrated in **Figs. 5A** and **5B**, removing the code words **408** having binary code decimal

equivalents **404** of 10 and 21, respectively, would ensure that no single code word **408**

10   was directly interdependent with more than two other code words **408**.

With reference now to **Figs. 6A-6F**, the groups of interdependent code words

remaining after the code words **408** having binary code decimal equivalents **404** of 10 and

21 were removed are illustrated. In particular, it can be seen that removing the binary

code having a decimal equivalent **404** of 10 results in a chain of code words **408** in which

15   the greatest number of code words directly interdependent with any one code word is two.

(**Figs. 5A** and **6A**). That is, no one code word **408** has more than two neighbor words.

Likewise, the removal of the code word having a decimal equivalent **404** of 21 from the

second group results in a chain of code words **408** in which no more than two code words

directly interdepend with any one code word (**Figs. 5B** and **6B**). It will further be noted

20   that **Figs. 5C-5F** are identical to **Figs. 6C-6F**. This is because the groups illustrated in

Figs. 5C-5F had no code words with which more than two other code words

interdepended, and therefore no code words within those groups were removed from the

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code space.

As explained above, according to one embodiment of the present invention, user values **400** must next be allocated to the code words remaining in the code space. In particular, user values **400** should be allocated such that the occurrence of one or more

5 dominant errors during the transmission of an original signal **200** results in a received signal **208** having a user value within the maximum tolerable deviation of the user value of the original signal **200**.

With reference now to **Figs. 7A-7F**, examples of how user values **400** may be assigned to the code words included in the groups illustrated in **Figs. 6A-6F** is shown. In

10 general, because in the present example the maximum tolerable deviation is one user value, the user values are assigned in linear series such that movement among the states of each group due to the occurrence of one or more dominant errors results in a received signal **208** that is within the maximum tolerable deviation.

With reference now to **Fig. 8**, the user values **800**, binary code decimal

15 equivalents **804**, and binary codes **808** incorporating the assignment of user values shown in **Figs. 7A-7F** to the groups of binary codes shown in **Figs. 6A-6F** are illustrated. For those code words **808** that did not appear as part of a group of interdependent code words (**Figs. 6A-6F**), the assignment of user values **800** may be random. In column **812**, the neighbors, in terms of user value **800**, is noted for each code word **808**. The maximum

20 variance for the code words **808** having neighbors **812**, in terms of the difference in user values, is summarized in column **816**. From **Fig. 8**, it can be appreciated that the maximum user value variance **816** between an original signal **200** and a received signal

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208 due to the occurrence of one or more of the dominant events identified for the communication channel **204** of the system is +/- 1. Accordingly, the maximum variance in the user value **800** has been constrained to the maximum tolerable variance defined for the system.

5   In the example code illustrated in **Fig. 8**, two code words were eliminated in order to achieve the desired maximum tolerable deviation. As a result, 30 user values **800** are available, yielding an effective code space of $\log_2 (30) = 4.9$ bits. This compares to a code space consisting of 12 valid code words resulting in a $\log_2 (12) = 3.5$ bit code space if the code words susceptible to alteration due to the occurrence of a dominant error were

10   removed from the initial code illustrated in **Fig. 4**.

According to one embodiment of the present invention, the ability of the system to tolerate at least some deviation between the original signal **200** and the received signal **208** may be used to increase the efficiency of the code scheme. For example, up to two user values may be assigned to any one code word within the example system discussed

15   in connection with **Figs. 4-8**. Therefore, by reordering the code illustrated in **Fig. 8**, the effective code space can be increased to $\log_2 (32) = 5$ bits. An example of such a reordering is illustrated in **Fig. 9**, which contains 32 user values **900** (0-31) allocated among the 30 available binary codes **904**. In particular, the reordered code illustrated in **Fig. 9** allocates the code word **808** having a decimal equivalent of 30 to user values **900**

20   28 and 29, and the code word **908** having a decimal equivalent of 31 to user values **900** 30 and 31. For each of the user values **900** having a shared binary code **908**, the shared value is listed as a neighbor **912**. However, it will be noted that the maximum variance

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916 remains at +/- 1. Accordingly, the number of user values **900** equals the number of

possible binary codes **908** for maximum efficiency, without violating the selected

maximum tolerable deviation. Furthermore, as with the code illustrated in **Fig. 8**, the

maximum tolerable deviation is maintained at the desired level, even when the dominant

5   errors of the system occur, without requiring the use of redundant bits.

It will also be noted that the additional user values added in **Fig. 9** are at the upper

range of those user values **900**. This is advantageous because, values 28 and 29 are,

according to the illustrated coding scheme, indeterminate from one another, as are user

values 30 and 31. This ensures that the maximum user value inaccuracy introduced by

10   assigning two user values to a single code word is as small as possible, as the smallest

percentage change between user values occurs at the upper range of those values.

Although the foregoing discussion has been in terms of integer user values, the

present invention is not so limited. In particular, any numerical increment or non-

numeric value may be assigned to the user values. Furthermore, when determining the

15   maximum number of neighbor words that any one code word can have, that number can

be determined by converting the maximum tolerable deviation to an equivalent distance

between code words and multiplying by two.

From the above description, it can be appreciated that the present invention may

be used in connection with any numbering system. Therefore, it can be applied in

20   connection with m-ary codes, and is not limited to binary codes such as those in the

examples given above.

Furthermore, it should be appreciated that the present invention may be used in

connection with any system used in the transmission of data that is characterized by having dominant errors, and that can tolerate at least some deviation between an original signal and a received signal.

According to the present invention, a method and apparatus concerning a high efficiency, error minimizing code are disclosed. In particular, the present invention provides for a high efficiency code scheme that does not require the use of redundant characters.

The foregoing discussion of the invention has been presented for purposes of illustration and description. Further, the description is not intended to limit the invention to the form disclosed herein. Consequently, variations and modifications commensurate with the above teachings, within the skill and knowledge of the relevant art, are within the scope of the present invention. The embodiments described hereinabove are further intended to explain the best mode presently known of practicing the invention and to enable others skilled in the art to utilize the invention in such or in other embodiments and with various modifications required by their particular application or use of the invention. It is intended that the appended claims be construed to include the alternative embodiments to the extent permitted by the prior art.